Insert: This application is a continuation of PCT Application No. PCT/GB99/01105, which is hereby incorporated herein by reference in its entirety.

OPTICAL FIBRE LASER

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This invention relates to optical fibre lasers.

Optical fibre grating lasers are attractive alternatives to the already well established semiconductor technology because they are cheaper to manufacture, exhibit narrow line width for ultra high resolution sensing and excellent wavelength stability provided by the grating. Furthermore they are fibre compatible, making all-fibre systems for telecommunication possible.

Of the fibre lasers demonstrated to date the simplest is the all-fibre grating DFB (distributed feedback) or DBR (distributed Bragg reflector) laser. Demonstrations of DFB fibre lasers of different cavity configurations and pump schemes have been reported on several occasions [1-3]. The first of these demonstrations showed lasing in two orthogonal polarisation modes. Later publications of DFB lasers claimed to provide a single polarisation output, but none has appeared to demonstrate a good qualitative understanding of the requirements for truly single mode output (single frequency and single polarisation).

Of the previously reported writing techniques one publication claims to introduce what is believed to be a birefringent π-phase-shift in the centre of the structure [4] caused by post-processing with high intensity pulses provided by excimer laser UV-sources (193 nm and 248 nm). The birefringent phase shift will then apply more to one polarisation than the other, hence causing that polarisation mode to reach the threshold for lasing before the other mode.

Twisting of the DFB fibre lasers and thereby an introduction of a circular birefringence has also been shown to cause the fibre laser to operate in a single polarisation [5]. This state of operation is then a function of the fibre twist and therefore the amount of circular birefringence introduced in the cavity. Furthermore Hi-Bi fibres have been shown to cause a significant [6] discrimination between the two polarisation modes with the result of allowing only one of the modes to lase.

However, there is still a need for a technique for generating robustly single polarisation DFB lasers.

This invention provides a method of fabricating a substantially single-polarisation optical fibre laser, the method comprising the step of exposing an optical

fibre to a transverse writing light beam to form a grating structure in a section of the optical fibre, the writing light beam being polarised in a direction not parallel to the axis of the section of optical fibre so that the induced grating structure has a different grating strength for two orthogonal polarisation modes of the fibre, the grating structure comprising a discrete phase shift which is substantially identical for the two orthogonal modes.

In embodiments of the invention, by writing substantially an entire fibre laser with UV-light polarised *perpendicular* (or at least non-parallel) to the fibre axis, a difference in grating strength between the two orthogonal modes of the fibre is introduced. This provides strong polarisation mode discrimination and so a robust single polarisation fibre laser operation can be achieved. We show lasers of length 5 cm and of approximate grating strengths (κL) of ~ 8. The lasers have a discrete π-phase shift in the structure off-centre by 5 mm giving a ratio of grating strength ratio of 2:3 on either side of the phase shift.

Optical phase conjugation has been attracting considerable attention, because of its application in the compensation of chromatic dispersion and nonlinearities in optical fibre communication systems using midspan spectral inversion (MSSI) technique[10], [11], and also because of its application in wavelength conversion which is essential in wavelength-division multiplexed (WDM) optical networks.

It has been conventionally accomplished by four-wave mixing *(FWM)* in a dispersion-shifted fibre (DSF) or a semiconductor optical amplifier (SOA), in which the optical signal is mixed with an externally injected pump light through a fibre coupler, and fed into a DSF or an SOA to generate a wavelength converted conjugate light. The signal and pump polarisation states must be aligned to get maximum conversion efficiency, which is generally not practical since any signal light polarisation fluctuation will affect the power of the conjugated light.

Two solutions have been proposed to achieve polarisation independence in the device. These are: (i) a polarisation-diversity arrangement [12], [13]; and (ii) injection of two orthogonally polarised pump lights[14], [15]. However, they add more complexity in the phase conjugator / wavelength converter.

FWM in a distributed-feedback (DFB) semiconductor laser [16] is attractive because it does not require external injection of the pump light, but its polarisation

independent implementation requires a phase-diversity arrangement [17].

The invention also provides an optical phase conjugator comprising:

one or more in-line optical fibre lasers for generating two substantially orthogonally polarised pump light beams; and

a non-linear mixing waveguide for receiving and mixing the pump beams with an input signal beam.

In this aspect of the invention, a novel phase conjugation and/or wavelength conversion technique by FWM is provided using orthogonally polarised pump lights - from inline fibre lasers. Embodiments of this technique feature polarisation independent operation and simple configuration without the need for external injection of pump light.

Further aspects and features of the invention are defined in the appended claims.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates the output spectrum of a single polarisation and single frequency DFB laser with 20 mW pumped power @ 980 nm;

Fig. 2 illustrates the so-called Poincare sphere output representation of the laser of Fig. 1;

Fig. 3a schematically illustrates the fabrication process;

Fig. 3b illustrates the use of such a laser as a frequency standard source;

Fig. 4a is a schematic diagram illustrating a phase conjugator / wavelength converter using a dual-polarisation fibre DFB laser;

Fig. 4b is a schematic diagram illustrating a phase conjugator / wavelength converter using two single-polarisation fibre DFB lasers;

Figs. 5a and 5b illustrate the output optical spectra of the phase conjugator / wavelength converter of Fig. 4a (using a dual-polarisation fibre DFB laser), where:

the fibre DFB laser operates at dual polarisations (Fig. 5a); and

the fibre DFB laser operates at a single polarisation (Fig. 5b);

Figs. 6a and 6b illustrate the output optical spectra of the phase conjugator / wavelength converter of Fig. 4b (using two single-polarisation fibre DFB lasers), where:

the polarisation states of the two pump lights are orthogonal (Fig. 6a); and the polarisation states of the two pump lights are aligned (Fig. 6b).

Theoretical background

Threshold and lasing conditions of DFB fibre lasers are functions of the grating strength (κL) where κ is the coupling coefficient and L is the length of the grating, and the gain available in the feedback structure.

For the core of an optical fibre to be photosensitive to UV light a certain amount of defects, or so-called Germano-Silica wrong bonds, must be present. The molecular characteristics of the wrong-bonds makes them susceptible for UV -light at a certain wavelength (e.g. 244 nm) to break the bond between them. The presence of wrong-bonds in the core of an optical fibre causes a stress that ideally should be isotropic. The presence of initial birefringence as is the case in most fibres however suggests a slightly anisotropic nature of the defects possibly generated by the drawing process of the fibres. The wrong-bond breakage introduced be the UV exposure causes a stress relief causing the refractive index to rise in the regions of the relief. A selective Ge-Si wrong-bond breakage therefore mainly will cause wrong-bonds polarised parallel to the polarisation of the light to be broken, and as result an anisotropic grating will be created in the core-region of the fibre.

Experimental set-up

The experimental set-up used to fabricate a prototype embodiment will now be described.

The DFB fibre lasers are written in a Deuterium loaded Er^{3+}:Yb^{3+} -doped fibre, to achieve increased pump absorption, with characteristics described elsewhere [8]. An intra-cavity frequency doubled Ar-ion laser operating CW at 244 nm with 100 mW output is used as the UV source. The grating forming the DFB laser was written using techniques and apparatus described in GB9617688.8, but other known techniques could instead be used. The initial horizontal linearly polarisation state of the laser was flipped to a vertical linearly polarised state using a $\lambda/2$-wave plate. The DFB grating was written with a π-phase shift (identical for both polarisations) off-centre [9] by 10% in order to maximise the output to one side of the laser. Up to 50

mW of light from a 980 nm diode was used as pump light. The laser was forward pumped and the polarisation state of the prototype laser was analysed using a HP 8905B polarisation analyser. The phase shift could of course have been different, for example many multiples of π.

Results for Prototype Laser

Fig. 1 shows the output spectrum of a 5 cm long single frequency, single polarisation prototype DFB fibre laser pumped with 20 mW @ 980 nm. The linewidth of the laser was measured to be as low as 3 kHz. An output power ratio of 30 dB between the output ends was observed. Being properly temperature stabilised the laser showed stable output power (3.1 dBm $\pm$ 0.05 dBm) for ~ 50 mW pump @ 980 nm and stable single polarisation operation over a period of hours. Fig. 2 shows the Poincare sphere output of the laser and shows that the degree of polarisation is 1, indicating single polarisation operation. The laser was also pumped with 1480 nm and showed despite the lower output power also single polarisation output.

The laser written with the UV light polarised orthogonal to the fibre axis were tested against a laser written with a birefringent phase-shift (only orthogonal polarised UV writing beam in the phase-shift region) as has been the only recently demonstrated writing procedure. See for example reference [20], where a two-step process is required to achieve a working single polarisation laser, and the process is subject to degradation as the tuned phase shift decays in time. We found that the all birefringent laser showed more stable single polarisation operation than the birefringent phase-shift laser. In particular for higher pump powers showed the birefringent phase-shift DFB occasional dual polarisation mode operation.

The fabrication process is summarised in Fig. 3a, which illustrates a section 10 of a photosensitive optical fibre 20 being exposed via a phase mask 25 to a writing light beam 30 which (in this example) is polarised substantially orthogonally to the axis of the section 10.

Fig. 3b illustrates an application of such a laser as part of a frequency standard device. If the laser is arranged to operate simultaneously at two wavelengths but one polarisation then these wavelengths $\lambda 1$ and $\lambda 2$ will be separated by $\Delta\lambda$. This

can be achieved by overlaying two DFB grating structures or by writing simultaneously as a Moire phase shifted structure. This difference can be detected as an RF beat frequency between the two output wavelengths.

It can easily be shown that $\Delta\lambda$ is proportional to $\lambda 1$ (or $\lambda 2$). So (as illustrated in Fig. 7) by monitoring $\Delta\lambda$ using an optical detector 200 and an RF frequency detector and applying the result via a feedback circuit 210 (e.g. comparing $\Delta\lambda$ with a reference RF signal RF_{ref}) to a wavelength control of the laser 220 operation (e.g. a temperature control), great stability in the wavelength of the two outputs of the laser can be achieved.

A further application of such a laser will now be described.

Figs. 4a and 4b show the configuration of a phase conjugator / wavelength converter. The converter uses FWM pump sources 100, 110, 120 which are Er^{3+}:Yb^{3+} fibre DFB lasers [18] pumped with 980nm 100mW laser diodes (LD's). Preferably the lasers are fabricated as described earlier.

To achieve polarisation independence, the FWM pump lights should preferably be orthogonally polarised at equal powers [14], [15], so these embodiments use either (a) a dual-polarisation fibre DFB laser (Fig.4(a)), or (b) two single-polarisation fibre DFB lasers cascaded through a polarisation controller (PC) 130 (Fig.4(b)).

Since the fibre DFB lasers are transparent at the signal wavelength, the signal and the DFB generated FWM pump lights are combined through direct injection of the signal light into one end of the fibre DFB laser. This eliminates the need of a polarisation combiner and a signal/ pump coupler as required in a conventional polarisation independent device. After amplification by an Er3+-doped fibre amplifier (EDFA) 140, the signal and pump lights are launched into a dispersion shifted fibre (DSF) 150, generating a conjugate light which is insensitive to the signal polarisation owing to the two orthogonally polarised pump lights. Optical isolators 160 are also used to prevent unwanted reflections.

Figs. 5a and 5b show the output optical spectra of the phase conjugator/ wavelength converter using a dual-polarisation fibre DFB laser in Fig.4(a). The fibre DFB laser is 5cm in length, operating at 1548.7nm in two orthogonal polarisations separated by about 0.8GHz, due to the birefringence in the fibre DFB resonator, for this "imperfect" (i.e. practical prototype) laser. The optical powers of the two

polarisations are slightly different at the "free-running state", but they can be changed by applying a stress at the mid-point of the fibre DFB laser as a result of the anisotropic phase shift induced in the two birefringent axes. By proper adjustment of the strength, the orientation and the position of the stress, we could force it operate either in two polarisations with equal powers, or in a single polarisation. The half-width of the unpumped DFB resonator stop band is measured to be about 0.2nm. The pass band insertion loss of the DFB laser module including two isolators is about 2.7dB. This can be reduced to be as low as 1dB with better components and splices. A tuneable single frequency laser operating at 1550.5nm is used as a signal source, and a 11km-DSF with zero-dispersion wavelength at 1548nm is used as a non-linear FWM media. The output spectrum is measured using an optical spectrum analyser (OSA) (with 0.08nm resolution) with scanning with a maximum hold trace (solid) and a minimum hold trace (dashed). The signal polarisation state is varied arbitrarily over all states using a PC throughout the measurement. Figure 5(a) shows the output spectrum when the fibre DFB laser operates at dual polarisations. As expected, nearly polarisation independent phase conjugation was realised. Remaining polarisation dependency is about 0.5dB. When the fibre DFB laser operates at a single polarisation (Fig.5(b)), the conjugate light suffered large fading over 30dB.

Although the single polarisation lasers in this example did not employ the new fabrication technique described above, in other embodiments such a technique is used and provides associated benefits.

It should be noted that this particular example of dual-polarisation fibre DFB laser can not be used with the signal bit-rate of higher than 400Mbit/s, because the signal bit rate must be less than half of the frequency separation of two pump lights[15]. The frequency separation can be expanded to more than 40GHz using a highly birefringent $Er^{3+}:Yb^{3+}$ fibre[18].

Figs. 6a and 6b show the output optical spectra of the phase conjugator/ wavelength converter using two single-polarisation fibre DFB lasers cascaded through a PC, as shown in Fig.4(b). The fibre DFB lasers are operating at 1548.7nm (pump 1) and 1550nm (pump 2) in a single polarisation using the above stress method. Incident FWM pump powers into the DSF are set to be equal by adjusting respective 980nm pump powers of the fibre DFB lasers. Note that the

isolators before and after the PC are not essential. Fig. 6(a) is when the polarisation states of two pump lights are set to be orthogonal by adjusting the PC between the two fibre DFB laser modules. The PC was actually set to minimise the mixing products between pump 1 and pump 2 appearing at 1547.4nm and 1551.3nm. The signal wavelength is set at 1549.5nm between pump 1 and pump 2. In this case, many mixing products are generated owing to the completely non degenerate FWM process, and the phase conjugate components to the signal appear at 1547.9nm conjugate 1, 1549.3nm conjugate 2, and 1550.5nm (conjugates). A solid trace is when conjugate 1 reaches a maximum, and a broken trace is when it reaches minimum. It is observed that conjugate 2 is polarisation independent, and one of conjugate 1 and conjugate 3 reaches maximum when the other reaches minimum. The remaining polarisation dependency of conjugate 2 is about 0.5dB. Figure 6(b) is when the polarisation states of two pump lights are set to be aligned to maximise the mixing products between pump 1 and pump 2. Conjugate 2 is found to have a large polarisation dependency over 20dB, although the maximum conversion efficiency is improved by 5.3dB compared to that in Fig.6(a), which agrees well with the theoretical value of 6dB. The signal wavelength can be set far from pump wavelengths, but the conversion efficiency becomes poor due to the non ideal zero-dispersion wavelength of the DSF.

In summary, a novel technique for optical wavelength conversion and phase conjugation by fibre FWM using inline fibre DFB lasers as orthogonally polarised pump sources has been described. It features substantially polarisation independent operation and simple configuration without the need for a polarisation combiner and a signal/ pump coupler as required in a conventional polarisation independent device. Polarisation independent operation of the phase conjugator/wavelength converter has been described, to achieve a polarisation dependency as low as 0.5dB. It is also possible to integrate the fibre DFB laser module into an EDFA. Furthermore, this technique is applicable to FWM in an SOA or in a chalcogenide fibre as well as in a DSF.

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